Revue des Composites et des Matériaux Avancés-Journal of Composite and Advanced Materials
Vol. 36, No. 2, April, 2026, pp. 293-302
Journal homepage: http://iieta.org/journals/rcma

Optimization of Concrete Mechanical Properties by Using Sawdust Ash as Cement Replacement and Waste Fibers as Reinforcement

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https://doi.org/10.18280/rcma.360207

Received: 10 January 2026
Revised: 26 February 2026
Accepted: 9 March 2026
Available online: 30 April 2026

Keywords:
date palm fibers, metallic and non-metallic reinforcement, optimal strength, sawdust ash, sustainable concrete, waste steel sheet fibers

ABSTRACT

In recent years, fiber-reinforced concrete has been widely used due to its superior performance compared to conventional concrete. The study investigates the influence of different ratios for non-metallic date palm fiber (DPF) and metallic waste steel sheet fiber (WSSF) on the mechanical properties of optimal sawdust ash concrete (OSDAC), in which 5% of cement in M30 grade concrete is replaced with sawdust ash (SDA). Laboratory tests were conducted to evaluate compressive, splitting tensile, and flexural strengths. DPF fibers are integrated at concentrations of 0.5% and 1%, whilst WSSF fibers are added at 0.25% and 0.45%, in relation to the concrete volume. A total of 135 specimens on cubes, cylinders, and beam structures were assessed for compressive, split tensile, and flexural strength at 28, 56, and 90 days, with nine samples allocated per test and fiber percentage. Both fibers types enhanced mechanical performance. WSSF fiber exhibited significant improvements in compressive, split tensile, and flexural strength relative to plain OSDAC, 8.8%, 51.9%, and 72.97% at 28 days, and 5.68%, 47.38%, and 67.9% at 56 days, and 5.63%, 44.7%, and 61.23% at 90 days, respectively, for a WSSF content of 0.45%. Correspondingly, the increases for DPF fibers were 3.4%, 41.2%, and 90.6% at 28 days, and 3.22%, 35.8%, and 87.2% at 56 days, and 3.21%, 35.6%, and 81.23% at 90 days, respectively, for a 1% DPF concentration. The results confirm that fiber-reinforced OSDAC is a feasible option for providing a sustainable alternative that lowers CO_2 emissions.

1. INTRODUCTION

The construction industry faces significant challenges due to rapid urbanization, depletion of natural resources, and the environmental impact associated with cement production, which is a major contributor to greenhouse gas emissions. Conventional concrete, although widely used, has inherent limitations, including a high carbon footprint, brittle behavior, low tensile strength, and susceptibility to cracking, which raise durability and service-life concerns. To address these challenges, the use of supplementary cementitious materials (SCMs) derived from industrial by-products has emerged as an effective approach to reduce cement consumption while enhancing durability and environmental performance. Additionally, the use of fibers—natural, recycled, or industrial—has been shown to improve crack control, tensile capacity, toughness, and post-cracking behavior of concrete. The combined use of SCMs and fibers offers a promising strategy to simultaneously address performance deficiencies and sustainability concerns. However, most existing studies have primarily focused on single SCM or mono-fiber systems, while the integrated performance of hybrid combinations remains insufficiently studied. In particular, limited research has investigated the combined incorporation of sawdust ash (SDA) with date palm fiber (DPF) and SDA with waste steel sheet fiber (WSSF) within a unified concrete matrix, especially regarding their synergistic effects on strength development, toughness, and post-cracking stability. Therefore, this study aims to cover the gap by a systematic approach to evaluate the mechanical features of hybrid fiber-supported concrete incorporating SDA. Moreover, the pozzolanic activity of SDA changes the microstructure, reduces pore connectivity, and improves resistance to chloride ingress, carbonation, and sulfate attack, thereby contributing to durable and sustainable infrastructure. To enhance sustainability, SDA, a byproduct of timber companies, has been examined as a supplement to cement. There are recent studies that recommend moderate SDA replacement levels that yield optimum performance. Majeed [1] described that enhanced mechanical and transport elements of foamed mortar at 20% SDA with damage beyond 30% replacement as a result of increased porosity. Fahad et al. [2], in the same vein, established that the combination of SDA and eggshell powder improved compressive strength by up to 29.58% at 0–20% substitution, whereas higher replacement levels showed reduced performance. Cheah and Remli [3] again established the possibility of using wood waste ash in concrete. Dhull [4] also observed a decrease in workability and compressive strength as the proportion of SDA increased, which was attributed to the highly porous nature of SDA particles, with higher water absorption and porosity.

In contrast, Elinwa et al. [5] demonstrated the pozzolanic activity of SDA by finding that it contains over 73% of SiO_2, Al_2O_3 and Fe_2O_3. However, their findings also revealed that, at cement replacement levels of 5%, 10%, and 15%, the 28-day compressive strength decreased to approximately 93%, 78%, and 68% of the control mix, respectively. Although SDA contributes to beneficial pozzolanic reactions, these contradictory findings suggest that its effectiveness is strongly influenced by the replacement ratio, highlighting the need for systematic mix optimization prior to its use in structural applications [5, 6].

Consequently, methodical mixture optimization is needed for structural applications. DPF is a low-cost, readily available natural fiber primarily used in non-structural mixtures. To allow its use in structural cementitious mixtures, approaches must be developed to mitigate its adverse effects on compressive strength [7]. Treated DPF can be used as a natural reinforcement fiber in concrete, offering significant improvements in thermal insulation, composite and acoustic performance [8, 9]. However, its application in structural concrete may reduce compressive strength. Processed and treated DPF has been shown to improve flexural performance, reduce density, enhance thermal performance, and improve acoustic performance. Prior studies [10-17] report that flexural strength enhancements may range from 20% to over 100%, depending on fiber treatment, dosage, and length. These enhancements are mainly attributable to the crack initiation and propagation under tensile loading [18, 19].

WSSF in concrete has been broadly reported to enhance the mechanical performance, particularly tensile and flexural strength, through the effective crack- bridging and energy absorption mechanisms [20, 21]. Numerous studies indicate that a fiber volume fraction of about 1% can enhance flexural strength by almost 20% [22, 23], thereby reducing crack development, which extends its life and results in long-term cost savings of up to 35% in some instances [24]. Based on fiber quantity fraction, steel fiber-reinforced concrete (SFRC) is generally classified into low (<1%), moderate (1–2%), and high (>2%) fiber content, which correspond with the shrinkage control, structural improvements, and impact/blast-resistant usage. Bhutta et al. [25] indicated that in relation to shrinkage control, structural improvement, and impact/blast-resistant usage, respectively. They also indicated that fiber geometry will significantly influence flexural performance, with end-regulated fibers to offer the most pliable response in geopolymer composites. Liu et al. [26] showed that substantial enhancements in elastic modulus and flexural tendencies of ultra-high routine geopolymer concrete, with an increment in elastic modulus and flexural behavior of ultra-high performance geopolymer concrete with SF content. Nguyen et al. [27] further indicated that macro twisted steel fibers (0–2%) can improve both the tensile strength and self-sensing ability in both pre- and post-cracking phases. Likewise, Zhang et al. [28] found that SF contents of up to 1% can effectively enhance the impact resistance, mitigating the microcrack effect.

Overall, previous investigations demonstrate that incorporating fibers—particularly steel fibers at 1–2%—significantly improves flexural, tensile, and impact performance through enhanced crack resistance and ductility, while reducing maintenance costs by 20–35%. The combined use of steel fibers with sustainable materials such as SDA and DPF offers a viable pathway for developing durable, high-performance, and eco-efficient concrete. Although DPF can enhance flexural strength by up to 60–85% at 1% dosage [29], it may reduce compressive strength and density at higher contents due to its hydrophilic nature and weak matrix compatibility [30, 31]. In contrast to previous studies that focused solely on the effect of SDA in concrete, this study investigates the combined incorporation of SDA with fibers (DPF and WSSF) to evaluate their synergistic influence on the mechanical performance of sustainable high-performance concrete.

The major contributions concerning this study may include the following:

- To investigate the application of SDA-DPF and SDA-WSSF as a sustainable option to improve the compressive, flexural, and splitting tensile strength of concrete.
- To assess the impacts of SDA-DPF and SDA-WSSF on the interfacial bonding between aggregate and cement paste under different loads.
- To analyze the effect of various SDA-DPF and SDA-WSSF proportions on hardened concrete, with special focus on mechanical performance.
- To evaluate the ecological and economic impacts of supplementing SDA-DPF and SDA-WSSF in the projected concrete to reduce the environmental impact associated with standard production.
- To determine the optimum mixture of SDA-DPF and SDA-WSSF to improve mechanical performance and assess the economic benefits of applying sustainable, locally processed materials in modern buildings.

The purpose of this study is to develop eco-friendly concrete using readily available, inexpensive resources. This contributes to reduced CO_2 emissions and promotes materials recycling.

2. EXPERIMENTAL WORKS

2.1 Materials and methods

This study used locally sourced materials to produce high-performance concrete, incorporating sustainable materials to enhance mechanical performance while reducing reliance on conventional components. The study used Ordinary Portland Cement (OPC, Grade 43) in accordance with IS 8112: 1989 [32], together with natural river sand obtained from the river and crushed coarse aggregate (20 mm) to produce fine and coarse aggregates. Natural sand and crushed aggregate were used to ensure quality and structural stability. Tap water was used in accordance with IS 456:2000 [33] for curing and mixing purposes. These materials are shown in Figure 1, the OPC, the fine aggregate, and the coarse aggregate. Sawdust obtained from sawmill waste was dried to eliminate remaining moisture, burned under controlled conditions, cooled, and sieved to produce SDA. SDA was then applied to partially substitute OPC at 5%, 10%, 20%, and 30% by weight. Chemical analysis established that the combined content of SiO_2, Al_2O_3, and Fe_2O_3 surpassed the minimum requirement outlined in IS 3812:2003 [34]. Thereby validating SDA as an appropriate pozzolanic material. Fiber preparation was then carried out. DPF were washed, dried, and manually separated and cut into specified lengths, and chemically treated by immersion in a 3% NaOH solution for 3 hours to improve compatibility and interfacial bonding with the cementitious matrix, as reported by Ali-Boucetta et al. [35]. WSSF were selected in accordance with ACI 544 recommendations ACI 544.1R-96 [36], and were prepared, dried, and cut into lengths of 20-30 mm, widths of 0.3–0.6 mm, and a thickness of approximately 1 mm to enhance tensile and flexural resistance and reduce crack initiation and proliferation. The preparation and configuration of these sustainable reinforcing materials are presented in Figure 2, while the physical properties of the fibers are summarized in Table 1. Finally, after preparing all materials, concrete mixtures were prepared following standard procedures, cast in steel molds, compacted, and water-cured at 23 ± 2 °C until the selected testing ages. Mechanical properties were evaluated by compressive, flexural, and splitting tensile strength tests at approximately 28, 56, and 90 days, using consistent protocols.

(a) Ordinary Portland cement (b) River sand (c) Crushed coarse aggregate

Figure 1. Materials used in concrete production

(a) Sawdust ash (b) Date palm fibers (c) Waste steel sheet fibers

Figure 2. Sustainable materials

Table 1. Physical properties of the reinforcing fibers

Fiber Type	DPF	WSSF
Surface	Corrugate	Plain
Cross section	Circular	Rectangular
Anchorage	Straight	Straight
Length (mm)	20-30	20-30
Diameter (mm)	0.3-0.6	0.2-1
Aspect ratio	50-66	30-100
Bulk Density (kg/m³)	512.2-1088.8	7850

Note: DPF = date palm fiber; WSSF = waste steel sheet fiber

2.2 Preparation of specimens

Plain concrete (PC) was prepared using natural aggregates (both coarse and fine) and Ordinary Portland Cement (OPC 43) with a 0.45 water-cement ratio. OSDAC was prepared by substituting 5% of cement with SDA, based on experimental findings. Four concrete mixes were prepared, each incorporating 0.5% and 1% of DPF, as well as 0.25% and 0.45% of WSSF. Based on previous studies on a simple concrete basis [15, 29-31], this proportion of metallic and non-metallic fibers was considered. Following the preparation of the defined concrete mixes, a systematic analysis of their mechanical properties was carried out. Specifically, 45 cubes (150 × 150 × 150 mm^3) were fabricated first, followed by 45 cylinders (150 × 300 mm^2), and then 45 beams (100 × 100 × 500 mm^3), totaling 135 samples. Each set unified different fiber proportions. This specimen preparation enabled the indication of the optimum fiber usage. The blending process was conducted as follows: firstly, the coarse cumulative and the DPF were then supplemented to the mixer, the DPF were immersed in water for 24 hours, and then air-dried in the mixing, this took place before it was added to the final blend. These procedures were required to prevent the fibers from being absorbed in excessive amounts of blending water during casting. Secondly, fine aggregate, cement, and sawdust ash were then supplemented to the mixer to ensure even distribution of non-metallic fibers. Conversely, for blending the metallic fiber, it was added in batches, then blended for 1 good minute, finally, water was added, and mixing continued for an additional 1-2 minutes to complete the process [37-39]. Next, after the mixing and casting, the specimens were left in molds for about 24 hours, and then demolded after 24 hours. After that, they were placed in a curing bath at 23 ± 2°C for 28, 56, and 90 days, respectively. Before testing, the specimens were air-dried for 24 hours. Assessment occurred on days 28, 56, and 90. The blending ratios for 1 m3 of concrete for various substitution ratios are shown in Table 2. These steps are necessary to ensure reliable curing and testing situations for all the samples.

Table 2. Mixing details ratio for 1 m^3 of concrete

Material	PC	OSDAC	0.5% - Fibre	1% - Fibre	0.25% - Fibre	0.45% - Fibre
Water (kg/m^3)	196	196	196	196	196	196
OPC (43 grade) (kg/m^3)	436	414	414	414	414	414
Coarse aggregate (kg/m^3)	1309	1309	1226	1220	1293	1291
Fine aggregate (kg/m^3)	655	655	613	610	647	646
SDA Content (kg/m^3)	_	22	22	22	22	22
		Fiber content (by volume of concrete)				
DPF (kg/m^3)	_	_	12	24	_	_
WSSF (kg/m^3)	_	_	_	_	6	10.8

Note: PC = plain concrete; OSDAC = optimal sawdust ash concrete; OPC = Ordinary Portland Cement; SDA = sawdust ash; DPF = date palm fiber; WSSF = waste steel sheet fiber

Table 3. Description of phase testing of a total of 135 test specimens

Phase	Samples	Age at Testing	Fibers Percentage	Purpose of Casting: Compressive Strength (Cube) N	Compressive Strength (Cube) Size (mm)	Tensile Strength (Cylinder) N	Tensile Strength (Cylinder) Size (mm)	Flexural Strength (Beam) N	Flexural Strength (Beam) Size (mm)
Reference	OSDAC	28 Days	0% of fibers	3	150 ×150 × 150	3	150 × 300	3	100 × 100 × 500
		56 Days		3	150 × 150 × 150	3	150 × 300	3	100 × 100 × 500
		90 Days		3	150 × 150 × 150	3	150 × 300	3	100 × 100 × 500
Phase 1	DPF-0.5-SDA	28 Days	0.5% of date palm fibers	3	150 × 150 × 150	3	150 × 300	3	100 × 100 × 500
		56 Days		3	150 × 150 × 150	3	150 × 300	3	100 × 100 × 500
		90 Days		3	150 × 150 × 150	3	150 × 300	3	100 × 100 × 500
	DPF-1-SDA	28 Days	1% of date palm fibers	3	150 × 150 × 150	3	150 × 300	3	100 × 100 × 500
		56 Days		3	150 × 150 × 150	3	150 × 300	3	100 × 100 × 500
		90 Days		3	150 × 150 × 150	3	150 × 300	3	100 × 100 × 500
Phase 2	WSSF-0.25-SDA	28 Days	0.25% of waste steel sheet fibers	3	150 × 150 × 150	3	150 × 300	3	100 × 100 × 500
		56 Days		3	150 × 150 × 150	3	150 × 300	3	100 × 100 × 500
		90 Days		3	150 × 150 × 150	3	150 × 300	3	100 × 100 × 500
	WSSF-0.45-SDA	28 Days	0.45% of waste steel sheet fibers	3	150 × 150 × 150	3	150 × 300	3	100 × 100 × 500
		56 Days		3	150 × 150 × 150	3	150 × 300	3	100 × 100 × 500
		90 Days		3	150 × 150 × 150	3	150 × 300	3	100 × 100 × 500

2.3 Mix proportions

The experiments were conducted in two different stages to assess the mechanical properties of the altered concrete. In the first stage, the samples containing 0.5% and 1% DPF with OSDAC, labeled as 'DPF-r-SDA' (where 'r' denotes the DPF percentage), were obtained. For each sample, 18 cubes for compression, 18 cylinders for tension, and 18 beams for flexural strength were prepared and tested at 28, 56, and 90 days.

Similarly, the second stage produced 'WSSF-r-SDA' samples containing 0.25% and 0.45% WSSF with OSDAC, with 'r' indicating the WSSF percentage. For each sample, another set of 18 cubes, 18 beams, and 18 cylinders was prepared and tested for the same strength parameters at the specified ages as indicated in Table 3.

3. RESULTS AND DISCUSSION

3.1 Effect of date palm fiber and waste steel sheet fiber on the compressive strength of optimal sawdust ash concrete

Compressive strength (CS) is one of the most important mechanical properties of concrete. It is commonly used to evaluate concrete performance. Numerous key factors impact CS, including cement content, aggregate properties, water-cement ratio, compaction and curing extent, and admixture type. This study assessed the role of several sustainable materials on compression strength by evaluating 150 × 150 × 150 mm³ concrete cubes preserved in water for 28, 56, and 90 days, as shown in Figure 3.

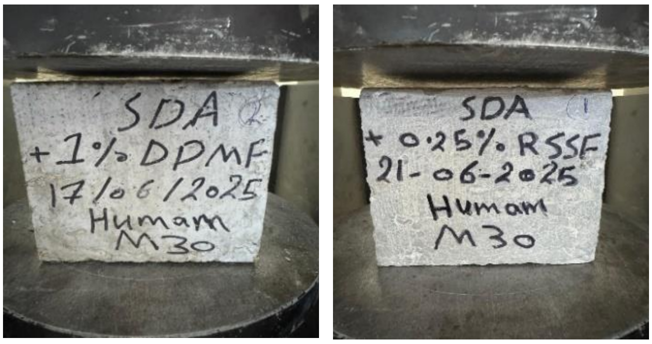

Figure 3. Specimens of compressive strength

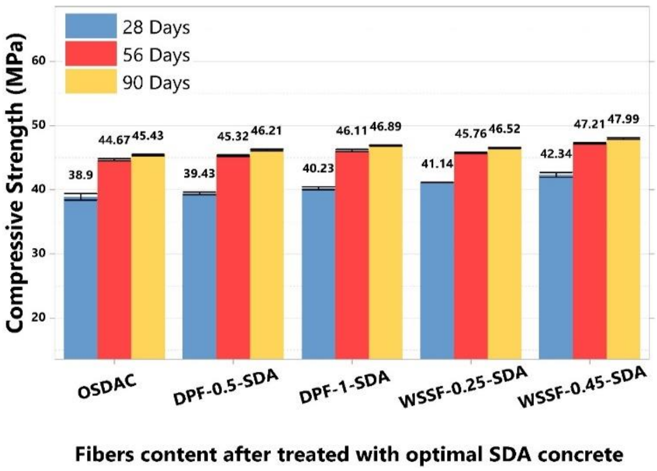

Figure 4. Compressive strength of various mixed fibers in relation to OSDAC

Note: Error bars represent the standard deviation of three replicate specimens. OSDAC = optimal sawdust ash concrete.

CS increases with increasing WSSF content, as shown in Figure 4. The proportion improvement in CS of WSSF-0.25-SDA and WSSF-0.45-SDA, with respect to OSDAC, is shown in Table 4. SDA, when used as a partial replacement for cement, SDA at low concentrations (5–10%) enhances CS through its pozzolanic activity and its capacity to react with calcium hydroxide, forming additional $C-S-H$ gel, whereas excessive amounts generally result in structural weakness.

Incremental increases of 5.7%, 2.44%, 2.4%, 8.8%, 5.68%, and 5.63% in CS were observed for WSSF-0.25-SDA and WSSF-0.45-SDA at 28, 56, and 90 days, respectively, compared with OSDAC, as shown in Figure 4 and Table 4. This is attributed to the presence of steel fibers, which enhance mechanical bonding strength and, consequently, delay the initiation and propagation of microcracks. The essential addition in the CS of OSDAC was made owing to supplementation and propagation. The addition of steel fibers improves the strength of OSDAC and allows the samples to show higher peak strength than the normal specimen, so the supplementation of steel to the changed concrete (OSDAC) shows enhancement in strength, as WSSF fiber was able to withstand axial loads and enhance matrix stiffness, as well as their resistance to deformation under loads.

WSSF-reinforced concrete showed improved performance. This is primarily due to the internal confinement effect and the high elastic modulus of the steel fibers, about 200 GPa. Under axial compression, the concrete matrix undergoes transverse lateral expansion, Poisson’s effect, and the high-stiffness WSSF resists internal tensile stresses, efficiently limiting the matrix and delaying micro-crack coalescence. Similarly, as listed in Table 4, the relatively low modulus of DPF and the hydrophilic nature cause an altered failure mode. DPF performs as a soft inclusion within the rigid cement paste. Furthermore, the propensity of natural fibers to form clusters at higher amounts makes local regions of high absorbency and air entrapment. These regions work as stress concentrators rather than stress transfer bonds, causing the resulting decrease in compressive strength when compared to WSSF-reinforced samples.

Previous studies, such as Althoey et al. [29], reported that 0.2% or 0.6% steel fiber (without sawdust ash) had little impact on compressive strength. In contrast, steel fiber with sawdust ash (WSSF-0.45-SDA) increased compressive strength by up to 8.8% in this study, compared to a 9.60% compressive strength increase with 1% steel fiber (without sawdust ash) [29]. Swarna et al. [40] also observed gradual increases in compressive strength with the addition of steel fibers.

For DPF-0.5-SDA, CS increased by 1.3%, 1.5%, and 1.7% at 28, 56, and 90 days, compared to OSDAC. For DPF-1-SDA, the increases were 3.4%, 3.22%, and 3.21% at 28, 56, and 90 days, as shown in Figure 4 and Table 4.

The limited effect of DPF on compressive strength is due to its compressive weakness and tendency to clump and distribute unevenly in the cement matrix. These factors create weak zones and reduce the matrix's ability to withstand compressive stresses.

Althoey et al. [29] also found 0.2% and 0.6% DPF had minimal effect on compressive strength. Here, DPF-0.5-SDA increased CS by 1.3%, and DPF-1-SDA achieved a 3.4% increase, less than the previously reported 8.01% with 1% DPF (without SDA).

3.2 Effect of date palm fiber and waste steel sheet fiber on the splitting tensile strength of optimal sawdust ash concrete

The splitting tensile strength (TS) test was conducted in accordance with the IS 5816:1999 using 150 mm × 300 mm concrete cylinders as indicated in Figure 5. The results showed a significant increase in tensile strength at 28, 56, and 90 days. This improvement is due to progressive changes in hydration, moisture, and micro-alterations in the cement-diluted structure during curing age. In addition, several factors influence this behavior. Especially, the water-to-cement proportion, aggregate quality, sample condition during testing, and curing quality. It is also observed that the applied load during the tensile test of the samples results in cracks. These cracks normally start at the sample center and propagate towards the loading points. Then, the crack gap increases with an additional transverse dislodgment. These observations provide insight into the damage progression of the tested specimens, reflecting the behavior of the developed mix.

Figure 5. Specimens of tensile strength

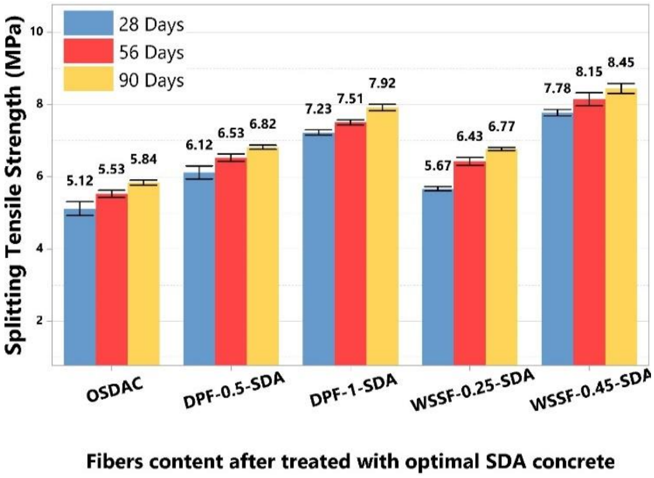

Figure 6. Tensile strength of various mixed fibers in relation to OSDAC

Note: Error bars represent the standard deviation of three replicate specimens

Accordingly, OSDAC samples produce sudden energy release, which is later released after the highest tensile strength load is attained. This action indicates the brittle failure in the OSDAC concrete. Compared with the OSDAC, the WSSF-SDA concrete showed a delayed crack initiation of opening at the highest tensile stress. This is due to the fact that the WSSF bridges cracks and inhibits their further spread. The results presented in Figure 6 and Table 4 clearly indicate that the role of inclusion in enhancing the TS of OSDAC concrete. The improvement ratio for the projected TS was obtained to be higher than the compression strength. The samples of WSSF-0.45-SDA indicated the peak enhancement in the TS, while the samples of the highest WSSF-0.25-SDA displayed less improvement in TS. The average TS of WSSF-0.45-SDA and WSSF-0.25-SDA increased by 51.9%, 47.38%, 44.7%, 10%, 16.27, and 15.9% at 28, 56, and 90 days, respectively, compared to OSDAC.

Randomly distributed steel fiber increased TS and protected cracks, bridging the cracks. Thus, when applying an allowable load on the beam whose concrete includes steel fiber. It controls the crack propagation of these cracks and causes more cracks to lead to the ultimate failure. It is similar to maximizing the applied load for typical testing specimens and likely due to the greater volume of non-metallic fibers and their corrugated geometry, promoting mechanical interlocking and effective post-cracking crack control. However, the compliant and hydrophilic nature of DPF, along with reduced mix homogeneity and increased porosity, limited its contribution to compressive strength. This agrees with the previous study, which concluded that a higher steel fiber content leads to a greater increase in tensile strength [29]. Again, Althoey et al. [29] observed a similar tendency of the steel fiber supplementation in this study. Through a comparison of this work with previous studies, it has been found that in the samples having WSSF, the maximum. improvement is up to 43% of the split tensile strength was attained with 1% steel fibers [29]. In contrast, steel fiber with sawdust ash (WSSF-0.45-SDA) increased tensile strength by up to 51.9% in this study. Najm and Ahmad [41] also observed a 71.26% increase in tensile strength with 1% steel fibers and ceramic materials, whereas with WSSF-SDA, it was enhanced by 51.9% (WSSF-0.45-SDA). In another study [42], the effect of steel fiber on the TS of concrete was investigated and yielded similar conclusions.

Based on the comparison between previous studies and the present study, it was observed that the TS in specimens containing steel fiber only (without SDA) was enhanced by 42.9%, while in samples that contain WSSF-SDA, it was improved by 51.9% and 10% for (WSSF-0.45-SDA) and (WSSF-0.25-SDA), respectively. Based on that, a main conclusion can be drawn: the improvement in the TS of samples containing steel fiber. This is irrespective of whether the sawdust ash was very close to the improvement in the samples containing both components mentioned.

Table 4 and Figure 6 present the tensile-strength results for DPF-modified OSDAC, showing a significant enhancement due to the DPF fiber's crack-arresting ability. Maximum enhancement in the OSDAC tensile strength reached 41.2% for DPF-1-SDA relative to the reference concrete. DPF primarily acts as an energy absorber and a crack controller. This is achieved through new mix components that increase the concrete's volumetric strain capacity after cracking, based on its mechanical properties, by bridging cracks and enhancing post-peak behavior. Results for DPF are consistent with steel fiber observations by Althoey et al. [29]. Across studies, specimens containing only DPF (no sawdust ash) achieved up to 17% enhancement with 1% DPF, whereas lower fiber volume fractions (0.20% and 0.60%) did not significantly enhance the high-strength concrete, particularly with the use of date palm and polypropylene fibers [29]. In contrast, DPF combined with sawdust ash (DPF-1-SDA) resulted in a 41.2% increase in TS in this study. An alternative study observed a 3% increase in TS using 0.5% DPF alone, whereas DPF-0.5-SDA in this study showed a 10% increase [31]. It can be concluded that the improvement is that the TS of samples containing WSSF-SDA and DPF-SDA showed superiority over specimens containing fiber without SDA in the same model. In other words, fibers contribute to enhancing the interaction between the concrete main components, in addition to the cementitious matrix, and the role of the fibers in stress transfer. On the other side, pozzolanic ash increased paste density and reduced porosity, particularly in the interfacial zone, thereby enhancing bonding with both the natural and steel fibers [32]. In turn, the steel fibers provided high stiffness and effective crack confinement and load-bearing capacity, while the DPF improved post-cracking behavior. This structural synergy resulted in superior mechanical performance compared to mixes reinforced with DPF alone.

3.3 Effect of date palm fiber and waste steel sheet fiber on the flexural strength of optimal sawdust ash concrete

Flexural strength (FS) is a key parameter. Used to evaluate the influence of fibers on the performance of concrete. The specimens used for the FS test are shown in Figure 7. FS indicates the post-cracking capacity of concrete. Generally, higher stiffness leads to improved FS. Table 4 and Figure 8 show the FS results presented in this work. Steel fiber enhances the FS of OSDAC by improving the bond strength between SDA particles under flexural loading.

Figure 7. Specimens of flexural strength

In all specimens, FS increased with increasing steel fiber content, with the greatest increase observed at 0.45% steel fiber addition. Specifically, WSSF-0.45-SDA and WSSF-0.25-SDA exhibited increases of 72.97% and 43.2% in FS compared to OSDAC as a reference. Steel fibers are a key factor in fiber-reinforced concrete performance, which is aware of its superior performance, particularly OSDAC-steel fiber reinforced concrete, and is attributed to the effective dispersion of steel fibers. It is also responsible for the ability of steel fiber-reinforced concrete to sustain loads after matrix cracking. This way, crack formation and propagation are delayed through maximizing FS. The observations discussed earlier are consistent with those reported by Althoey et al. [29].

However, to further demonstrate these observations and for a comparison with previous studies, it indicates that FS in specimens containing only WSSF (without SDA) increased from 67% to 165% for 1% steel fiber [29], while specimens with WSSF-SDA showed enhancements of 43.2% to 72.97% (WSSF-0.25-SDA, WSSF-0.45-SDA). Najm and Ahmad [41] also reported increased FS of 33.34% to 70.37% (HK-1-WOC, HK-2-WOC) with steel fibers reinforced with ceramic materials. In specimens containing WSSF-SDA, the enhancement ranged from 43.2% to 72.97% (WSSF-0.25-SDA, WSSF-0.45-SDA).

Mohammadi and Kaushik [43] investigated the effect of crimped steel fibers on the FS of concrete. Comparison with the present study shows that FS in specimens containing only CR (without SDA) increased by 40.18–100.37%, while specimens with WSSF-SDA exhibited enhancements of 43.2–72.97% (WSSF-0.25-SDA, WSSF-0.45-SDA). DPF-0.5-SDA and DPF-1-SDA achieved increases in FS of 52.6% and 90.6%, respectively, compared with OSDAC as the reference model.

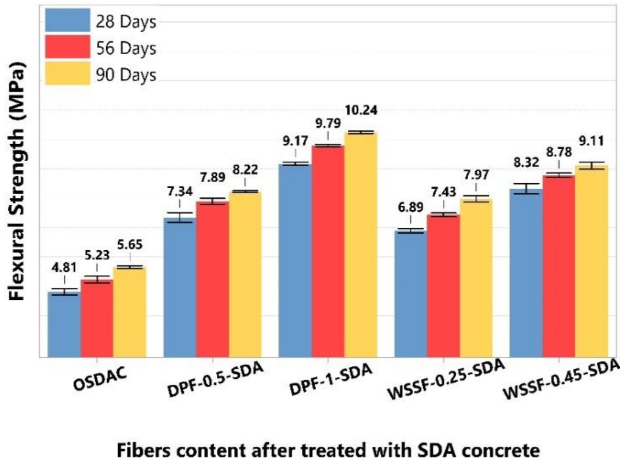

Figure 8. Flexural strength of various mixed fibers in relation to OSDA

Note: Error bars represent the standard deviation of three replicate specimens

Table 4 and Figure 8 present the FS results for specimens cured for 28, 56, and 90 days. These results suggest that fiber efficiency is strongly influenced by fiber stiffness, geometry, and dosage relative to the targeted load mechanism.

Table 4. Average compressive, splitting tensile and flexural strength tests for various mixes

S. No.	Sample Name	Compressive Strength (% var. w.r.t to Reference) MPa			Tensile Strength (% var. w.r.t to Reference) MPa			Flexural Strength (% var. w.r.t to Reference) MPa		
		28 Days	56 Days	90 Days	28 Days	56 Days	90 Days	28 Days	56 Days	90 Days
1	OSDAC	38.9	44.67	45.43	5.12	5.53	5.84	4.81	5.23	5.65
2	DPF-0.5-SDA	39.43	45.32	46.21	6.12	6.53	6.82	7.34	7.89	8.22
		1.3%	1.5%	1.7%	19.5%	18%	16.8%	52.6%	50.9%	45.5%
3	DPF-1-SDA	40.23	46.11	46.89	7.23	7.51	7.92	9.17	9.79	10.24
		3.4%	3.22%	3.21%	41.2%	35.8%	35.6%	90.6%	87.2%	81.23%
4	WSSF-0.25-SDA	41.14	45.76	46.52	5.67	6.43	6.77	6.89	7.43	7.97
		5.7%	2.44%	2.4%	10%	16.27%	15.9%	43.2%	42.1%	41.1%
5	WSSF-0.45-SDA	42.34	47.21	47.99	7.78	8.15	8.45	8.32	8.78	9.11
		8.8%	5.68%	5.63%	51.9%	47.38%	44.7%	72.97%	67.9%	61.23%

FS results for DPF are consistent with the findings of Althoey et al. [29]. Comparison with previous studies indicates that specimens containing only 1% DPF exhibited enhancements of 60% to 85% relative to the reference specimen [29], while specimens with DPF-SDA showed increases of 52.6% and 90.6% (DPF-0.5-SDA, DPF-1-SDA). These results suggest that the enhancement in FS for specimens with DPF alone is comparable to that of specimens with both DPF and SDA. The addition of DPF provides a connection link (bridging) effect in cementitious composites. This prevents crack initiation and progression and increases the material's flexibility.

Further, as specified by the high FS of WSSF in Table 4, these fibers primarily enhance ductility through a controlled bridge and pull-out mechanism. The high elastic modulus promotes WSSF to stitch macro cracks, where the energy is consumed by the frictional work required to debond the steel from the matrix.

It is worth noting that a review of the literature indicates that no prior research has examined the mechanical properties of WSSF concrete and SDA concrete.

4. CONCLUSION

This study investigates the combined use of SDA with natural and recycled fibers to enhance the mechanical performance of concrete.

- CS showed a noticeable improvement with increasing fiber content, attributed to improved fiber–matrix interaction.
- TS showed a noticeable improvement with increasing fiber content, with steel fiber mixes performing better than natural fiber mixes.
- FS improved with higher fiber content, particularly in mixes containing natural fibers. Natural fibers contributed to improved flexural behavior by increasing ductility and crack-bridging capacity in the concrete matrix.
- Steel fibers mainly enhanced compressive and tensile strength due to their high stiffness and load-bearing capacity. whereas natural fibers improved flexural behavior by providing ductility and efficient crack control.
- The combination of SDA with steel and natural fibers showed good mechanical performance, indicating effective interaction between materials.
- The developed mixes offer economic and environmental benefits by reducing cement consumption and promoting sustainable waste utilization.
- In conclusion, the study demonstrates that these mixes enable sustainable, high-performance concrete for structures.

ACKNOWLEDGMENT

This work was conducted under the supervision of Prof. K. Rambabu, whose expertise in research design and insightful guidance significantly contributed to the development of the methodology and analysis of this study. Sincere appreciation is also extended to the Department of Civil Engineering, College of Engineering, Andhra University, for its continuous academic support.

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APPENDIX

Abbreviation	Description
SDA	Sawdust ash
DPF	Date palm fiber
WSSF	Waste steel sheet fiber
OSDAC	Concrete made with 5% sawdust ash as a cement replacement
DPF-0.5-SDA	Concrete made with 0.5% date palm fiber and 5% sawdust ash as a partial cement replacement
DPF-1-SDA	Concrete made with 1% date palm fibres and 5% sawdust ash as a partial cement replacement
WSSF-0.25-SDA	Concrete made with 0.25% waste steel sheet fibres as a waste fibre and 5% sawdust ash as a partial cement replacement
WSSF-0.45-SDA	Concrete made with 0.45% waste steel sheet fibres as a waste fibre and 5% sawdust ash as a partial cement replacement
PC	Plain concrete
OPC 43	Ordinary Portland cement.
CS	Compressive strength
TS	Tensile strength
FS	Flexural strength